REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
June 2014	Technical Paper	June 2014- July 2014

4. TITLE AND SUBTITLE

Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Matthew R. Gilpin, David B. Scharfe, Marcus P. Young, Rebecca N. Webb

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q0CA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive.
Edwards AFB CA 93524-7013

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-TP-2014-166

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
Technical paper presented at 12th Annual International Energy Conversion Engineering Conference, Cleveland, OH, 28-30 July, 2014.
PA#14336

14. ABSTRACT
A bi-modal solar thermal system capable of providing propulsive and electric power to a spacecraft has been identified as a promising architecture for microsatellites requiring a substantial _V . The use of a high performance thermal energy storage medium is the enabling technology for such a configuration and previous solar thermal studies have suggested the use of high temperature phase change materials (PCMs) such as silicon and boron. To date, developmental constraints and a lack of knowledge have prevented the inclusion of these materials in solar thermal designs and analysis has remained at the conceptual stage. It is the focus of this ongoing research effort to experimentally investigate using both silicon and boron as high temperature PCMs and enable a bi-modal system design which can dramatically increase the operating envelope for microsatellites. This paper discusses the current progress of a continued experimental investigation into a molten silicon based thermal energy storage system. Using a newly operational solar furnace facility, silicon samples have been melted and results indicate that volumetric expansion during freezing will be the primary difficulty in using silicon as a PCM. Further experimental studies using different materials and test section fill factors have identified potentially reliable experimental conditions at the expense of energy storage density. In addition to conducting experiments, a concurrent computational effort is underway to produce representative models of the experimental system. The current models generally follow experimental results; however, difficulties still remain in determining high temperature material properties and material interactions. This paper also discusses the future direction of this research effort including modeling improvements, analysis of convective coupling with phase change energy storage and potential facility improvements.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Marcus Young
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	19	**19b. TELEPHONE NO** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**			661-275-6264

Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion

Matthew R. Gilpin*

University of Southern California, Los Angeles, CA 90089, United States

David B. Scharfe†

ERC Incorporated, Edwards AFB, CA 93524, United States

M.P. Young‡

Air Force Research Laboratory, Edwards AFB, CA 93524, United States

Rebecca N. Webb§

Air Force Research Laboratory, Edwards AFB, CA 93524, United States

A bi-modal solar thermal system capable of providing propulsive and electric power to a spacecraft has been identified as a promising architecture for microsatellites requiring a substantial ΔV. The use of a high performance thermal energy storage medium is the enabaling technology for such a configuration and previous solar thermal studies have suggested the use of high temperature phase change materials (PCMs) such as silicon and boron. To date, developmental constraints and a lack of knowledge have prevented the inclusion of these materials in solar thermal designs and analysis has remained at the conceptual stage. It is the focus of this ongoing research effort to experimentally investigate using both silicon and boron as high temperature PCMs and enable a bi-modal system design which can dramatically increase the operating envelope for microsatellites. This paper discusses the current progress of a continued experimental investigation into a molten silicon based thermal energy storage system. Using a newly operational solar furnace facility, silicon samples have been melted and results indicate that volumetric expansion during freezing will be the primary difficulty in using silicon as a PCM. Further experimental studies using different materials and test section fill factors have identified potentially reliable experimental conditions at the expense of energy storage density. In addition to conducting experiments, a concurrent computational effort is underway to produce representative models of the experimental system. The current models generally follow experimental results, however, difficulties still remain in determining high temperature material properties and material interactions. This paper also discusses the future direction of this research effort including modeling improvements, analysis of convective coupling with phase change energy storage and potential facility improvements.

I. Introduction

Solar thermal propulsion (STP) offers a unique combination of high thrust and high specific impulse (I_{sp}), which has long been predicted to offer significant advantages over chemical and electric propulsion systems in certain mission scenarios. Based on a 2009 survey of available propulsion systems, STP shows

*Ph.D. Candidate, USC Dept. of Mech. and Aerospace Engineering, 854 W 36th Pl, L.A., CA 90089, AIAA Member

†Staff Scientist, High-Payoff Propulsion, AFRL/RQRS, 1 Ara Rd., Edwards AFB, CA 93524, AIAA Member

‡Program Manager, High-Payoff Propulsion Concepts, AFRL/RQRS, 1 Ara Rd., Edwards AFB, CA 93524, AIAA Member

§Assistant Professor High-Payoff Propulsion Concepts, AFRL/RQRS, 10 E. Saturn Blvd, Edwards AFB, CA 93524, AIAA Member

strong potential for enabling high performance microsatellites.[1] An appropriately-sized solar thermal system could dramatically expand the microsatellite operational envelope by providing 1.5–2 km/s total ΔV to a 100 kg spacecraft. While these large ΔV missions are feasible with electric propulsion options, the response time for such a maneuver would be several years; in keeping with the typical microsatellite goal of rapid response, an STP system reduces this to a matter of days.

Multiple research efforts have targeted an STP based spacecraft over the concepts 50 year history. However, no solar thermal spacecraft have been flow to date. STP is traditionally viewed as an unproven technology with significant drawbacks including the requirement of solar illumination at the time of propulsion and the difficulty associated with integrating a dedicated thermal collection mechanism to an existing spacecraft bus.

To mitigate these issues, it has been suggested that a solar thermal propulsion system be combined with high performance thermal energy storage (to eliminate any timing constraints on propulsive maneuvers) and a means of thermal-electric conversion (to eliminate the need for a 'legacy' power system) in a bi-modal configuration.[2–6] With such a combined system, solar thermal energy could provide both propulsive and electrical power for a satellite. A technological review has indicated that effective thermal energy storage is the enabling technology for such a system and it is proposed that the latent heat of molten elemental materials can provide a robust, high temperature, and high density thermal energy storage solution.

The ongoing research effort presented here is focused on determining the feasibility of a bi-modal solar thermal propulsion system based on high performance energy storage. While previous solar thermal efforts have included a means of thermal energy storage, the key difference proposed here is the optimization of such a system utilizing a phase change material. Utilizing the latent heat of a storage material will allow for greater storage density and more predictable performance with a more stable operational temperature. This paper discusses the current state of the experimental and analytical effort to develop a proof of concept thermal energy storage system.

I.A. Augmented Solar Thermal Design for Microsatellites

A bimodal thermal storage system, including both a direct thermal output (i.e.: heated propellant gas) and a converted electrical output, can be optimized for a variety of applications both terrestrial and in-space. The particular application explored here is that of a microsatellite combined power and propulsion system. The design goals of such a system have been discussed previously,[2–5] and will only be briefly recapitulated here.

To favorably compete with existing technology on a 100 kg mircosatellite, a bimodal STP system must provide 100 W of continuous electrical power and have continuously available propulsion on the order of 1 N with an I_{sp} of 300–400 s. This level of performance can be achieved with an ammonia based solar thermal rocket, which has significant practical advantages over a rocket with often-proposed cryogenic H_2 propellant. To achieve adequate thermal storage temperatures (i.e. propellant temperatures), a solar collection mechanism with a concentration ratio of 10,000:1 is necessary and fiber optic coupling to the storage device is required to separate concentrator pointing from spacecraft attitude. Both of these technologies appear to be feasible based upon the current state of technological development.[4] Additional technological requirements such as advanced insulation and high performance thermal electric conversion also appear to have readily applicable solutions which can be drawn from previous research efforts.[5,6]

The remaining technological challenge for a bi-modal STP system is high performance thermal energy storage. Previous solar thermal efforts have included sensible heat thermal energy storage in their design by using high temperature materials such as graphite and boron carbide.[7,8] High energy densities can be achieved in this manner, however, the large ΔT required (ΔT of 600 K for 1.5 MJ/kg in graphite) can result in reduced thruster performance, increased thermal stress on the spacecraft, and lower thermal-electric energy conversion efficiency.

To avoid the drawbacks of sensible heat energy storage, augmenting a STP system with latent heat thermal energy storage is proposed. A new class of PCMs must be developed that have a properly matched melting temperature and a sufficiently high latent heat capacity. A survey of candidate PCMs has identified silicon and boron as the thermal storage materials of choice; several other candidate materials are listed in Table 1 for comparison.

Table 1: Potential high temperature phase change materials. Material specific references are given when applicable, otherwise, values are taken from database sources.[9–11] Thermal conductivity values given in italics are the closest available measurement to T_{melt}.

Material	T_{melt} [K]	ΔH^o_{fus} [kJ/kg]	k_{th} @ T_{melt} [W/mK]
MgF_2[12]	1536	940	3.8
Beryllium	1560	1312	*69*
Silicon[13]	1687	1785	20
Nickel	1728	292	*83*
Scandium	1814	313	*16*
Chromium	2180	394	48
Vanadium	2183	448	*51*
Boron	2350	4600	*10*
Ruthenium	2607	381	*80*
Niobium	2750	290	*82*
Molybdenum	2896	375	*84*

Interestingly, previous solar thermal propulsion research efforts have also noted the possibility of utilizing boron and silicon as a phase change materials (PCM).[14–17] However, development has been limited to brief conceptual studies often citing schedule constraints and the uncertainty of developing an entirely new technology as the reason for selecting sensible heat storage materials. For the present work, boron is identified as the ideal far-term storage material due to an extremely high heat of fusion and a melting temperature close to the optimal performance point for an ammonia based STP rocket.[18] It must be noted, however, that limited research has gone into handling boron in the molten state and the high melting temperature increases the cost of ground experiments by an order of magnitude. Therefore, silicon, is also targeted as a near term storage option, providing storage capacities on par with sensible heat systems and a storage temperature that will provide moderate thrust and specific impulse.

As noted above, bi-modal system must supply both propulsive and electrical power to the spacecraft. A comparison of state of the art thermal-electric conversion technologies indicates that thermophotovolatic (TPV) conversion is the best option for an augmented STP system based on a relatively high conversion efficiency and the ability to operate at high temperatures.[3] The stable, high temperature energy delivery of the proposed latent heat storage is well suited to thermophotovoltaic operation and a boron based system has peak emission wavelengths near the cutoff for existing InGaAs photovoltaic cells.

The performance of the proposed bi-modal system has been evaluated and has been shown to be advantageous potentially providing up to 60% more ΔV than a similarly sized monopropellant chemical system when using an advanced boron-based configuration.[5] Unlike previous STP development efforts targeting large scale spacecraft, the microsatellite platform amplifies the benefits of an STP system. The proposed scale is below the range of bi-propellant systems and is unable to generate sufficient electrical power for high thrust electric propulsion. Despite a long development history and definite advantages, multiple challenges still remain in order to ultimately produce a proof of concept demonstration of the proposed bi-modal technology. This paper presents the experimental and computational work that is ongoing to further develop the proposed latent heat thermal storage system.

II. Solar Furnace

A solar furnace facility has been constructed to perform experimental testing of high temperature latent heat thermal energy storage. To address the practical problems associated with the use of boron and silicon as phase change materials, an experimental approach is being taken with the ultimate goal of creating a proof of concept thermal energy storage system. Noting that the ultimate spacecraft design will require a “point” input of thermal energy in the form of concentrated sunlight (as opposed to uniform heating of

a conventional furnace), the existing solar furnace facility was built to ensure strong correlation between experimental efforts and potential future applications.

The solar furnace facility has progressed through four different iterations and is currently capable of performing molten silicon tests. Additionally, relatively minor facility improvements can be implemented to potentially allow for small scale molten boron testing.

II.A. Solar Furnace Design and Construction

The current USC solar furnace is a two stage system as diagrammed in Fig. 1. A computer controlled heliostat is used to re-direct sunlight into the solar concentrator mirror array. The concentrated sunlight is then focused through a fused quartz window into the testing chamber. Test sections loaded into the chamber can be held in a vacuum or a low pressure controlled environment to reduce convective losses and repress material interactions and oxidation.

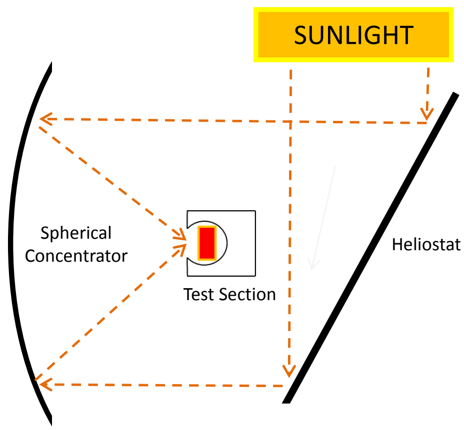

Figure 1: Two stage solar furnace path diagram.

Figure 2: USC heliostat mirror array.

The heliostat consists of an altitude-azimuth tracking drive, computer control system and 12 ft x 8 ft second surface mirror array. To keep costs low, the tracking drive was obtained as surplus from previous AFRL efforts and refurbished.[19] Open loop tracking rate control is performed using a supplied target vector and the local solar vector computed in real time via published algorithms.[20,21] The heliostat mirror array, shown in Fig. 2, is supported by an aluminum I-beam structure and uses aluminum honeycomb panels as a support surface for eight 4 ft x 4 ft second surface float glass mirrors. The mirror array's size was determined by the maximum space allowed at the current location and coverage requirements set by the concentrator. The placement of the solar furnace facility allows for approximately 4 hours of sunlight coverage per day.

The solar concentrator assembly is an array of four approximately 40 in by 40 in spherical mirrors arranged into a single optic with a radius of curvature of 124 in. The use of spherical mirrors for solar concentration is not ideal due to the influences of spherical aberrations on the maximum concentration ratio. However, the desire to keep construction costs low necessitated their use to gain sufficient scale. The selected mirrors were supplied as COTS stock by Display and Optical Technologies of Georgetown, TX from their Wide Angle Collimated (WAC) display program; the only custom work required was the design and construction of the mounting system and frame. Each mirror facet is a first surface aluminized mirror on a 0.5 in thick glass substrate. The mirrors are specified with a mean slope error of 180 $arcseconds$ from ideal and a proprietary SiO_2 based coating results in a reflectivity approaching 90% when weighted against the solar spectrum.

The mirror array, shown in Fig. 3, was aligned using a point source placed at the radius of curvature along the central optical axis. Each mirror was adjusted so that its reflected image collapsed onto the point source resulting in a single unified optic. An aperture curtain is used to mask off portions of the mirror array; the aperture is currently 70 in in diameter and provides a usable concentrator area of approximately 3600 in^2

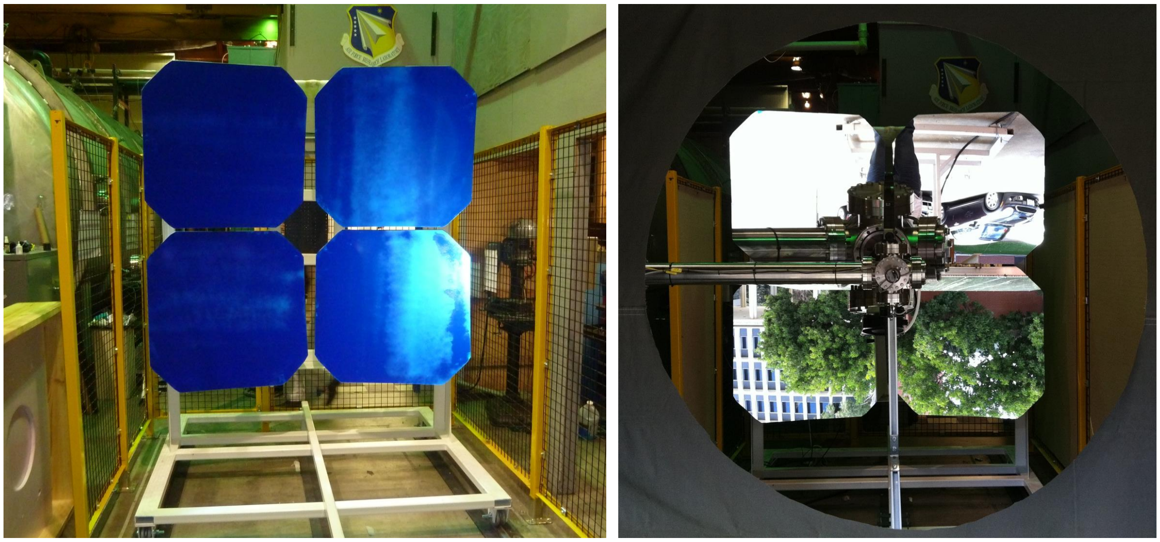

Figure 3: Photographs of the mirror array during construction (left) and as seen through the 70 inch aperture curtain. The mirrors are blue during construction due to a protective plastic film applied before shipment. Note the testing chamber seen in the middle of the concentrator array in the photograph on the right.

(2.3 m^2) when taking into account the central diagnostic mount and occlusion by the testing chamber.

The testing chamber for the USC solar furnace is a 6 *in* CF cross connected by an extension to a vacuum chamber outside the area of the solar concentrator. Concentrated sunlight enters the testing chamber through a 6 *in* diameter, 0.25 *in* thick fused quartz window. The testing chamber is instrumented with both Type K and Type C thermocouples for temperature measurement and an emissivity sensing non-contact infrared thermometer is also available. The infrared thermometer has been calibrated by the manufacturer for use through the quartz chamber window.

II.B. Current Facility Performance

The current solar furnace facility has been characterized for total output power as a function of solar insolation and individual component efficiencies. A ray-tracing code was written to determine the optimal experimental test article placement, taking into account the effects of spherical optics, the random slope error of the reflector, heliostat pointing and flatness error, incoming solar angle distribution, blockage from the test chamber, and the influence of the quartz window. To experimentally confirm the optimal location in the furnace, a CCD flux mapping diagnostic was developed that allows for the solar flux profile to be determined at planes along the optical axis. A lambertian target is placed at the plane of interest and imaged with a linear CCD calibrated against a blackbody. The resulting image is then processed to give the power distribution across the plane. In-plane CCD measurements matched predictions made by the ray tracing codes and it was determined that optimal experimental location is approximately 1.5 *in* back from the 62 *in* geometric focus.

At this location, flux maps given in Fig. 4 indicate peak concentration ratios in excess of 4000:1 and approximately 90% of total power at the plane included within a 1 *in* diameter spot. The end-to-end system efficiency of the USC solar furnace is relatively low at approximately 40% primarily due to quartz window losses and the use of commercial float glass mirrors on the heliostat.

Despite the low total system efficiency, power levels sufficient for molten silicon experiments are possible with the current furnace design. Figure 5 gives the power delivery to a test section vs. local direct-normal insolation and acceptable spot size. This data has been confirmed utilizing commercially available high flux laser power meters and scaled against measurements from an Eppley Pyrheliometer.

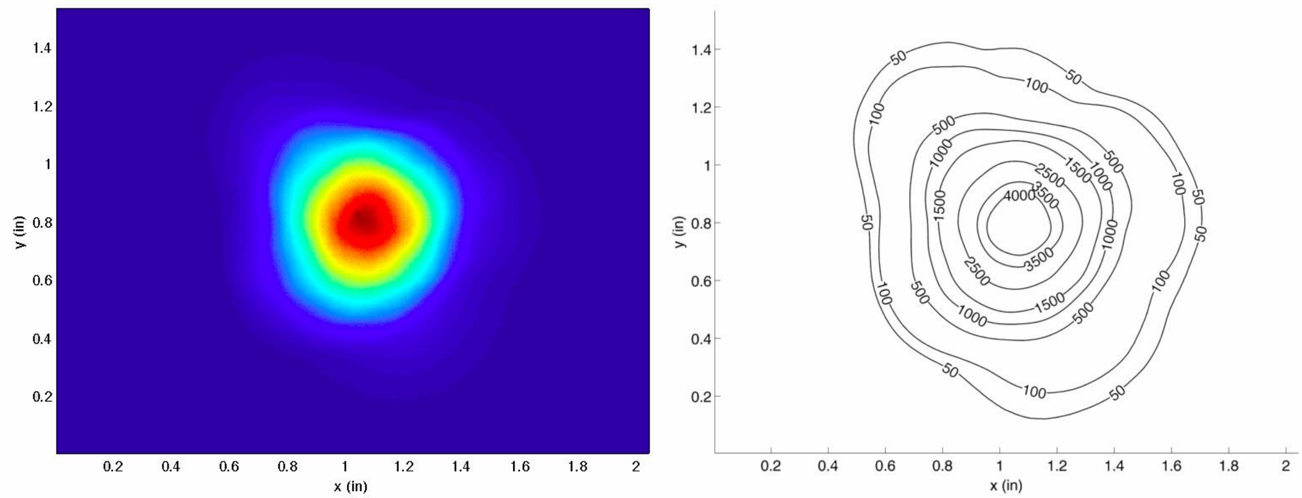

Figure 4: Flux maps taken at the experimental location for the USC solar furnace. Iso lines are given in number of suns.

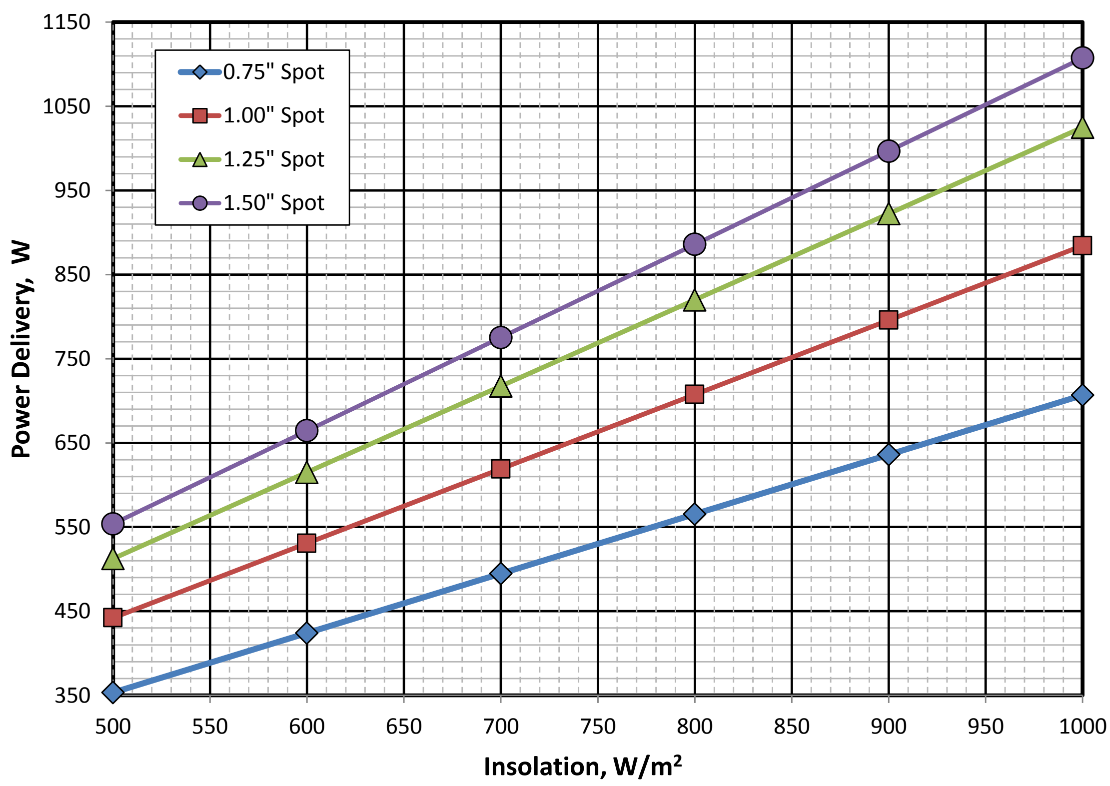

Figure 5: Power delivery vs. insolation for the USC solar furnace as a function of acceptable spot size. Values include losses from the quartz chamber window. Typical insolation at the facility is between 750-950 W/m^2 depending on atmospheric conditions.

III. Experimental Testing

High temperature latent heat thermal energy storage is frequently discussed in both the solar thermal and thermophotovoltaic literature.[17,22–24] Molten silicon in particular, has been identified in thermophotovoltaic research efforts as an "ideal" thermal storage material.[23] Despite a continued interest, no experimental efforts have investigated molten silicon thermal energy storage and all work to date has remained in the conceptual phase. This lack of development has precluded the use of silicon or boron in solar thermal development projects in favor of simpler, lower performance, sensible heat designs.

The goal of this research is to both experimentally and analytically investigate the use of silicon and boron as high temperature latent heat thermal storage materials for solar thermal propulsion and ultimately produce an experimental demonstration of silicon based thermal energy storage coupled to a propellant. This experimental effort is the most substantive investigation into high temperature latent heat thermal energy storage to date and the project will ultimately provide sufficient data to develop a practical understanding of a physical molten silicon based system.

III.A. Test Design and Proceedure

Experiments in the USC solar furnace currently utilize cylindrical test sections with the geometry shown in Figure 6. The cylindrical geometry is the product of over 80 investigative solar furnace testsand has been chosen for simplified modeling and ease of in-house manufacture. Since silicon is highly reactive in the liquid state, materials studies were conducted and identified boron nitride (BN) as a promising container material due to a self limiting reaction with molten silicon and synergy with potential molten boron container designs.[2–6] Test sections are designed for a minimum solar furnace input power of 750 W and are intended to provide straight forward system characterization and model validation as opposed to maximum thermal efficiency.

Test section construction begins by loading silicon into a cylindrical HBC grade BN container with a friction fit lid. HBC boron nitride was selected since it lacks a boric oxide binder which can precipitate at high temperatures.[25] The BN inner container is inserted into a graphite sleeve which uses a press fit to seal both the graphite and BN lid. Early furnace testing utilized either silicon powder or small silicon chips to load the BN container. With these materials, packing difficulty resulted in maximum silicon fill factors of approximately 60%. While these experiments were sized to contain over 30 g of silicon, the low fill factor resulted in little correlation with predictive models. As a result, current experimental size is not limited by furnace power, but by the availability of affordable silicon rod stock.

The primary insulation in the current design consists of commercially available Rescor 760 castable ceramic insulation. This ZrO_2 ceramic product is low cost, easy to cast, and has an acceptably low thermal conductivity (0.93 W/mK). The use of ZrO_2 ceramic in contact with graphite, however, places limits on the experiment due to reactivity at elevated temperatures. ZrO_2 and graphite react at temperatures as low as 1400 K. At peak experimental temperatures, the equilibrium pressure of the reaction is approximately 40 $torr$.[26] Before this reaction was identified, tests resulted in irreversible contamination of the quartz chamber entrance window. To prevent quartz window contamination at the expense of convection losses, current tests are operated in an environment of 150 $torr$ of argon. Testing using a pure BN system would allow for low pressure operation without quartz window damage. However, the high cost and relatively low thermal conductivity of BN compared with graphite makes this approach impractical during this effort. Test sections are instrumented by embedding Type K thermocouples into the cast ceramic and by running a bare wire Type C thermocouple through the ceramic sting mount as shown in Fig. 6.

The first step in the furnace testing procedure is to bake out new test sections under vacuum at approximately 500 K using a 1000 W spot lamp. This process evaporates proprietary water based binders from the Rescor 760 ceramic which can fog the quartz chamber window and decrease power delivery. The chamber is then backfilled to 150 $torr$ of argon and solar furnace power is gradually increased until the test section reaches thermal equilibrium. At this point, a shutter curtain is used to cut solar furnace power and the cooling curve for the test section is recorded.

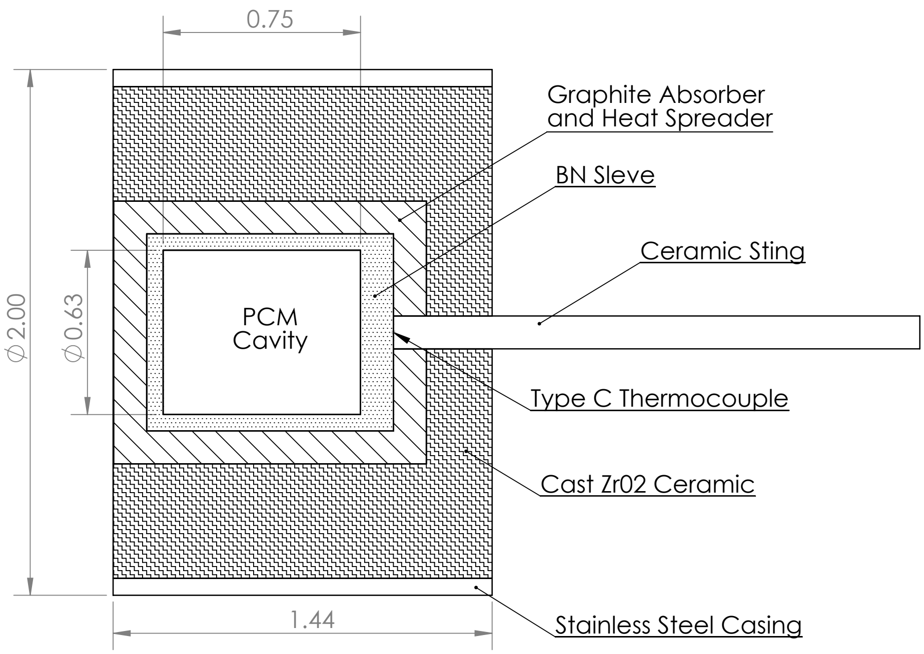

Figure 6: Cut-away diagram of a cylindrical test article sized for 9 g of silicon showing materials, components, and overall experimental geometry. Dimensions given in inches.

III.B. 100% Fill Factor Testing

Figure 7 shows experimental data taken during solar furnace testing for the geometry shown in Figure 6. The phase change process occurs approximately from t = 30 s to t = 120 s and demonstrates the relative temperature stability expected from a latent heat system. The curves "Cycle 1" and "Cycle 2" are taken from the same test section across two back-to-back cycles. Note that "Cycle 1" exhibits a temperature spike at t = 108 s. This spike corresponded with cracking of the test section due to asymmetric expansion of silicon and is likely a result of rapid freezing by a trapped liquid silicon mass. Repeated tests also demonstrated similar temperature profiles and cracking behavior.

Silicon is unique in that is is one of the few materials that expands during freezing and the resulting volume increase of approximately 10% poses significant challenges if silicon is to be used as a PCM.[27] The majority of current phase change materials used for thermal energy storage expand when melting (including boron) and this is typically resolved by incorporating an expansion area to accept and drain back the additional liquid volume during thermal cycling. Water is the only other material currently considered as a commercial PCM which undergoes freezing expansion and it is typically held in either open or flexible containers to prevent system damage. In the case of a silicon based system for satellite applications, a flexible or open topped container is not possible. When using a sealed and filled container, perfect re-solidification could theoretically return the silicon to the original shape. However, in practice asymmetrical freezing will lead to voids, trapped liquid volumes, and an decreased effective density. In industrial applications, the difficulties of asymmetrical silicon freezing are alleviated via precision control of thermal gradients leading to an approximately 1-D freezing front.[28,29] In the case of a thermal energy storage system, this approach is impractical as multiple heat paths out of the silicon container will yield multiple freezing locations. In order to prevent container damage when freezing, a silicon based latent heat system will have to employ a reduced fill factor, precise geometry to control heat flow, safeguards to prevent complete solidification or, more likely, a combination of all three. Despite being neglected in the majority of extant literature concerning silicon as a PCM, the issue of volumetric expansion presents the greatest difficulty for realizing an effective system.

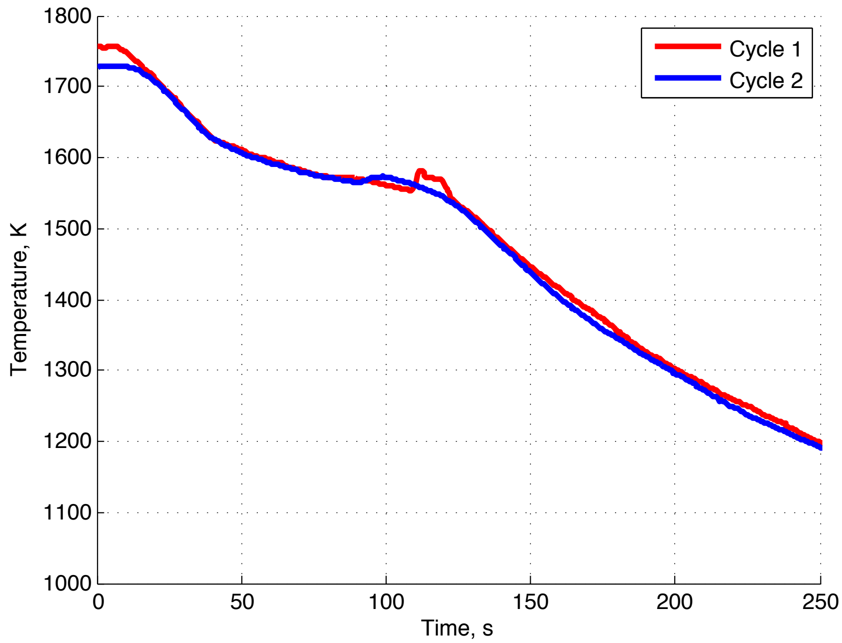

Figure 7: Experimental data taken with a Type C thermocouple as labeled in Figure 6. Both traces are from the same test section in back to back cycles. Note that "Cycle 1" has a temperature spike at approximately t = 108 s corresponding to the rapid freezing of trapped silicon.

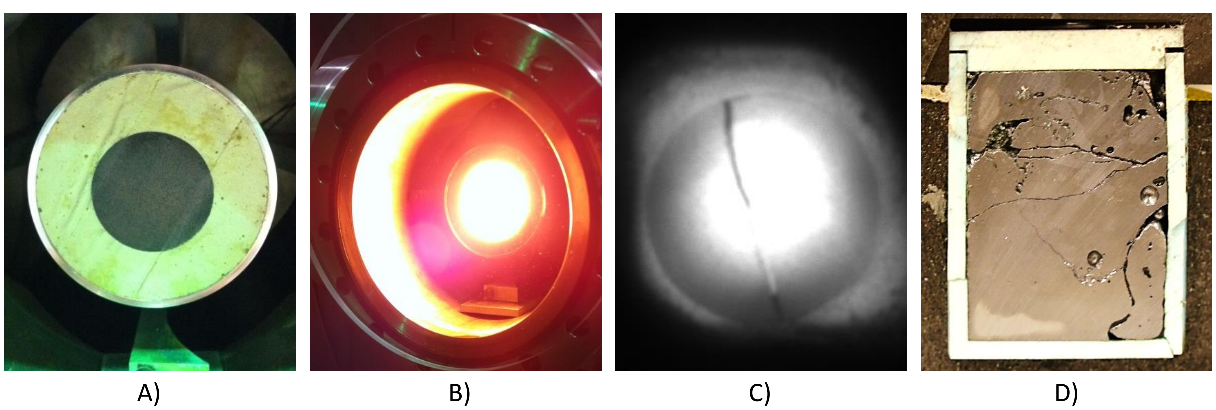

Figure 8: Photographs taken during 100 % fill factor tests. A) Test section before heating. B) Test section immediately after power cutoff. C) Infrared photograph taken during solar heating showing a large crack formed in the test section during the previous cooling cycle. Note the relative size and intensity of the solar furnace input. D) Image of the interior of the crucible after testing showing decreased silicon density after freezing

IV. Expansion Damage Mitigation

IV.A. Reduced Fill Factors

Following 100% fill factor testing, experiments were performed in the hope of establishing a reliable testing configuration that would allow for repeated testing without test section failure. The first step in this investigation was performing a series of tests utilizing the same geometry as in Figure 6 with gradually reduced fill factors. Tests were conducted with fill factors between 100% and 80% decreasing in 5% increments.

During this testing series no test sections with fill factors $< 100\%$ showed the macroscale damage seen during 100% fill factor trials. However, audible cracking during the phase change process provided an indication of internal test section damage. Once fill factors were reduced to 80% there was no longer audible cracking during the phase change process. However, when cut open and examined, it was seen that small cracks had still formed in the internal boron nitride liners.

An additional 80% fill factor test was completed with a test section constructed entirely with SIC-6 grade graphite (i.e. no BN liner) as a follow-on to materials investigations. Literature related to the industrial casting of large silicon ingots indicates that non-wetting behavior and carbon contamination on the order of $< 20\ ppm$ is possible using graphite crucibles provided that the graphite density is $> 1.75\ g/cc$ and that the graphite grain size is $< 50\ \mu m$.[30] SIC-6 graphite has a density of $1.85\ g/cc$ and a grain size of $10\ \mu m$ which is within these requirements. This all-graphite test section exhibited no audible cracking, showed no damage after multiple freezing cycles and indicated non-wetting liquid silicon behavior when sectioned. Further efforts will include additional SIC-6 testing due to the success in 80% trials. However, it must be noted that the contamination of the silicon bulk has yet to be examined.

Test sections used during fill factor testing also indicated interesting silicon freezing behavior. Since silicon is non-wetting to the BN sleve, the liquid silicon forms a "bead" within the test section during testing. Due to the reduced fill factor and the increase in density upon melting, this bead does not make contact with the upper ends of the container. The shape of silicon after testing, as shown photographed in Fig. 9, suggests that during the freezing process the front of the liquid "bead" freezes first as the front of the test section is responsible for the majority of heat loss. Once this freezes, the remainder of the liquid "bead" is isolated from the front of the PCM cavity. This causes freezing silicon to completely fill the rear of the test section until pressure caused by volumetric expansion cracks the front of the "bead" and the remaining liquid silicon is extruded to fill the front void.

IV.B. Partial Freezing

Another potential method for mitigating test section damage is to only allow for partial freezing of the silicon by re-introducing power to the system before complete solidification. This was attempted using a test section with a 100% fill factor and power was returned to the test section after 50, 60, and 70 seconds. All three of these intervals were successful and the test section indicated no audible cracking or physical container damage. Since it is estimated that the phase change process begins aproximately 30 seconds after cutting solar furnace power, the longest 70 second freezing interval represents roughly 45% of the total phase change process length and the total energy storage achievable in the test section is reduced accordingly. Further testing is required to determine the ultimate level of solidification possible.

While this method has potential for flight systems provided the duty cycle can be matched to the eclipse period on orbit, it proves problematic for solar furnace ground demonstrations. Since crucible failure is assued when the experiment is terminated, a limited number of cycles is possible with each test section. This is further constrained by the limited experimental time afforded by the placement of the USC solar furnace facility.

V. Computational Analysis

In parallel with uncovering practical problems associated with using molten silicon as a PCM, solar furnace testing is also inteded to determine the fidelity required of freezing kinetics models to capture essential system behavior. In order to gauge experimental performance, a computational model has been developed to predict the thermal behavior of test sections in the USC solar furnace. This model uses

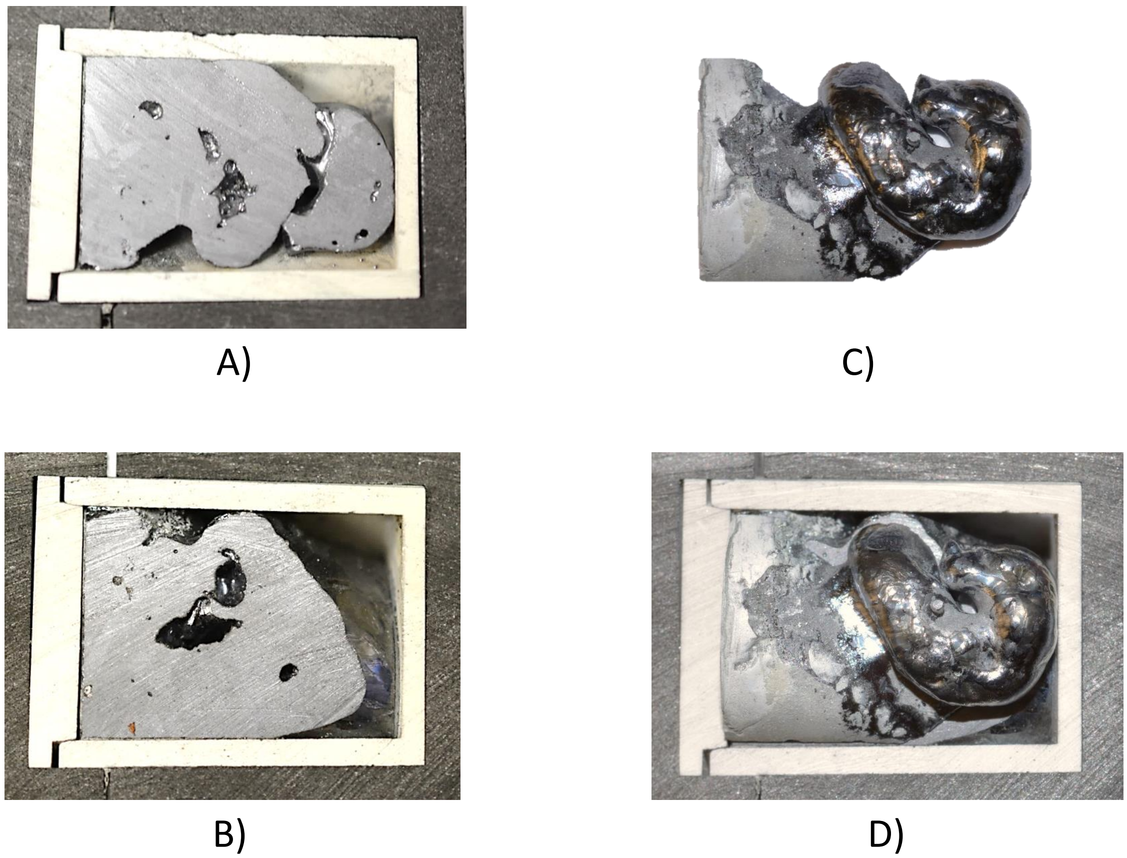

Figure 9: Photographs taken after sectioning an 80% fill factor solar furnace test article. The graphite absorber / heat spreader, boron nitride liner, and silicon are shown. Test section geometry is given in Figure 6. In all photographs the rear of the test section is on the left. A) Top half of the test article. B) Bottom half of the test article in a top down view as related to the test section as a whole. Note how the rear of the test section is filled and external voids are present at the front. C) Top half of the silicon removed from the top of the test article and flipped vertically. The formation towards the right indicates flowing liquid silicon. D) Top down view of the test article with silicon restored. It is apparent that after initial silicon freezing, liquid silicon was forced from the top of the test section.

SolidWorks Simulation Professional 2013 to solve for the initial steady state temperature distribution based on system geometry and known solar furnace input power. The resulting temperature distribution is then imported into MATLAB.

An in-house MATLAB model is used to predict the cooling performance (i.e. following a period of steady state operation at high temperature) of furnace test sections. The model is a cylindrical, axisymmetric, 2-D (r,z) simulation that uses a fixed-grid finite difference method to solve for the overall temperature profile of a test section as a function of time. The model has a similar formulation as that presented by Elgafy et al. and uses the "enthalpy method" to account for the phase change process.[31] For computational nodes containing the PCM, a latent heat value is assigned and treated as a source or sink when that node is within a temperature range defined as "mushy" zone. Once a node enters the "mushy zone," currently defined as $T_m \pm 0.1$ K, all energy leaving or entering the node is assigned to the phase change process and the node remains at a constant temperature. When a particular node exhausts the assigned latent heat energy during cooling, the temperature is allowed to change and sensible heat cooling resumes. This model neglects convective motion of the PCM when in the liquid state, assumes a 100% fill factor at all times, and neglects effects from density change during melting and freezing.

The MATLAB model uses radiative and convective boundary conditions for all outer surfaces. The radiation boundary condition is calculated using the radiosity method for all exterior nodes and considers the small shielding effect provided by the vacuum chamber. A ray tracing code was written to calculate the node-to-node view factors for the test section after reflection from the vacuum chamber (approximated as a cylinder). The ray tracing code produces an n x n matrix of view factors where n is the number of exterior radiating nodes by randomly launching and tracking 20 million rays distributed by total area. For example, the view factors calculated for node 1 would be F_{1r1}, F_{1r2}, $F_{1r3}...F_{1rn}$. View factors also take into account rays that require multiple bounces within the vacuum chamber to strike the crucible. The contribution of these rays to the view factor calculation is scaled by the reflectivity of the vacuum chamber and the number of required bounces. Using the calculated view factors, an energy balance is calculated at each time step in the model to determine the radiation output from the test section. Shielding calculations indicate an approximately 20% drop in radiation losses.

A natural convection boundary condition accounts for operation in the 150 *torr* argon testing atmosphere. Further assumptions in the MATLAB model include homogeneous and temperature independent material properties for all materials except from graphite and silicon and a neglect of thermal contact resistance.

Figure 10 shows the predicted cooling behavior for the test section geometry in Fig. 6 after it is brought to thermal equilibrium with a solar furnace input power of 750 W. Tempertaure profiles for the modeled region are given in Fig. 10 as a function of time and show an approximate freezing profile. Heat loss from all parts of the test section causes the silicon to solidify from all directions. Note that this assymetrical modeling treatment deviates from the one dimensional freezing considered in previous investigations of silicon as a PCM.[23] The MATLAB model shows that near the end of the freezing process, molten silicon will be encased in solid silicon resulting in high stress concentrations with the potential for container damage.[28] Container damage from these stresses has been experimentally demonstrated in this work.

Concurrently with the in-house MATLAB model, a COMSOL Multiphysics model using the same experimental geometry was developed at the University of Colorado Colorado Springs.[32,33] This model uses the "temperature transforming method" to account for the phase change process altering the specific heat of the PCM material within the "mushy zone" so that the resultant sensible heat cooling calculated by the simulation program accounts for the energy released during solidification. Like the in-house MATLAB model, the COMSOL model neglects density change, partially assumes isotropic material properties, assumes a 100% silicon fill factor, and considers radation shielding from the vacuum chamber.

The results of the MATLAB and COMSOL models compared with 100% fill factor data is given in Fig. 11. While both models follow the general trend of the experimental data, it is apparent that the model predicts a faster cooling rate than experiments. It is also important to note that the thermal conductivity of the boron nitride liner was reduced by an order of magnitude in the model to provide an adequate fit. Since the model neglects thermal contact resistance and the machining process does not yeild perfect mating of parts, this reduction can be justified. However, work is needed to determine a more accurate representation of material properties. In particular, there is no data availible for Rescor 760 at high temperatures under the present testing conditions.

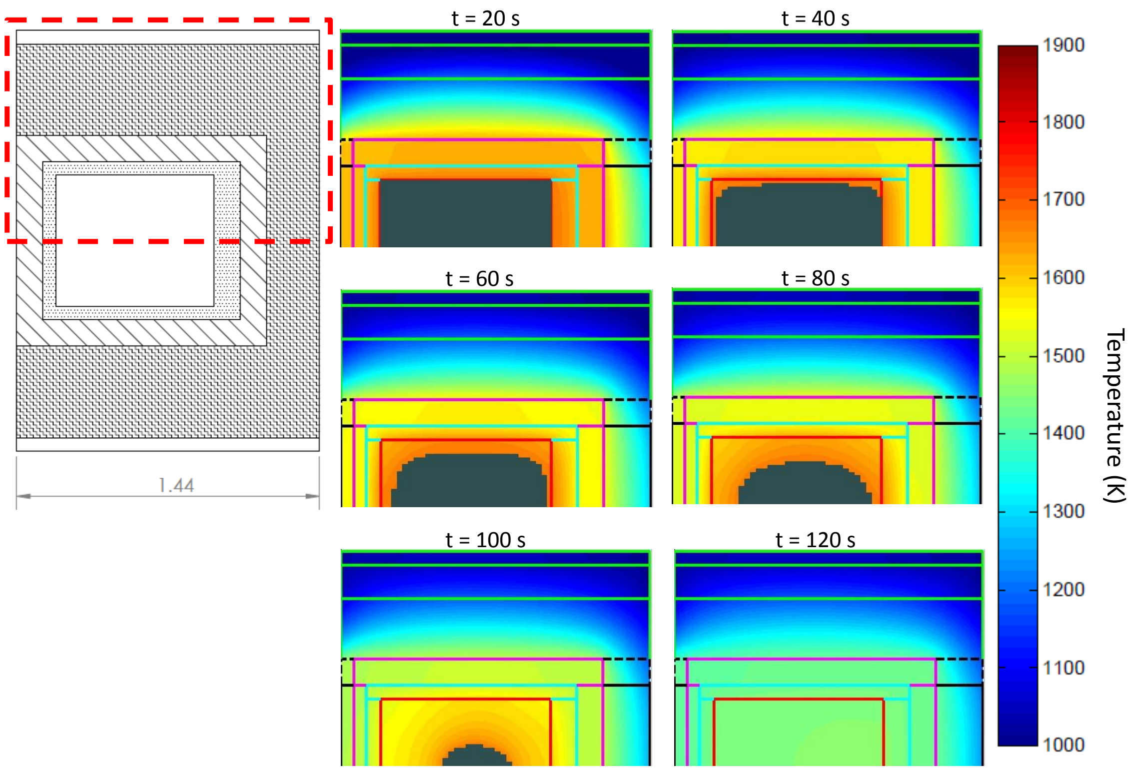

Figure 10: Thermal profiles as a function of time calculated by the in-house MATLAB model for the test section given in Figure 6. Note that the model is axisymmetric so the red outlined region of the cutaway drawing is the region represented by the thermal maps. Also note that grey is used in the thermal maps to represent liquid silicon and it is apparent that liquid silicon will become trapped during the freezing process.

The MATLAB model was also compared to experimental results for 80% fill factor testing as shown in Fig. 12. In order to approximate the effects of a lower fill factor, the latent heat availible to the MATLAB model was reduced by 20%. Similar to 100% fill factor tests, the MATLAB model over predicts cooling in the test section and the thermal conductivity of BN was reduced to provide an more adequate fit and approximate contact resistance.

While accuracy is limited by problems with material properties and broad assumtions concerning uniform properties and simplistic freezing model, both the MATLAB and COMSOL models are capable of demonstrating general behavior without a rigorous treatment of the silicon freezing process. This indicates modeling of a high temperature latent heat system with acceptable levels of accuracy is possible with existing modeling techniques and can be used to design futher experimental hardware for the USC facility.

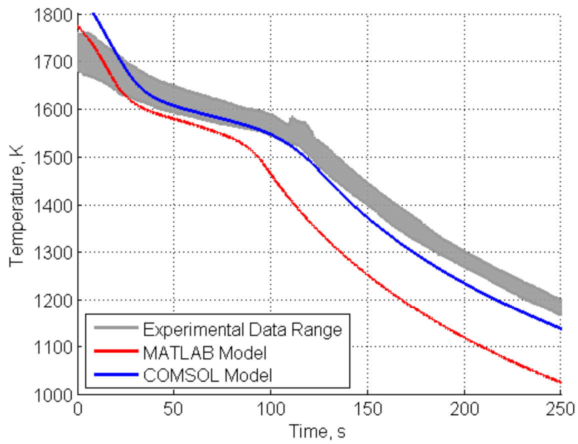

Figure 11: Comparison of experimental, COMSOL, and MATLAB data for 100% fill factor testing using the geometry given in Fig. 6. The experimental data range includes data across three test sections and 4 thermal cycles.

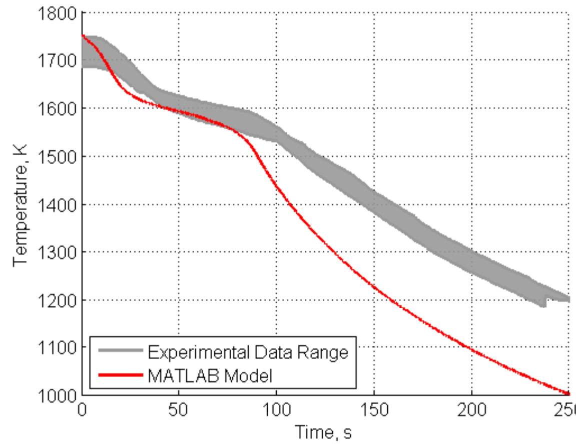

Figure 12: Comparison of experimental, COMSOL, and MATLAB data for 80% fill factor testing using the geometry given in Fig. 6. The experimental data range includes data across three test sections and 15 thermal cycles.

VI. Future Work

VI.A. Container Design and Modeling

Further experiments are needed to determine a reliable experimental condition that is capable of surviving multiple freezing cycles without sustaining damage from volumetric expansion of the silicon PCM. The success of tests using SIC-6 graphite indicates that experiments are possible with at least 80% fill factors. However, silicon contamination must be analyzed if this material is to be included in a potential spacecraft system.

Additionally, future testing is required with materials that wet with molten silicon (i.e. low density graphite) to determine bulk silicon contamination and the resulting effects on the freezing process. In a wetting environment, especially in a low gravity, the primary void within the PCM cavity would be centrally located as liquid silicon will be wicked to the container walls. This would allow for silicon to freeze from the outside in and the central void could potentially absorb the effects of volumetric expansion. Tube furnace testing as well as early solar furnace testing using NAC-500 grade graphite (1.72 g/cm, 203 μm grain size) has previously demonstrated the required wetting behavior with silicon fully coating the interior of the crucible after a thermal cycle.

The in-house MATLAB model will also be used to further investigate asymmetrical freezing. The model is currently being modified to accept tapered geometries similar to those proposed by Chubb et. al.[23] Chubb states that tapered geometries will provide a more stable emitter temperature for a TPV based system. However, the 1-D treatment of the phase change process neglects volumetric expansion as well as potential asymmetry due to the use of adiabatic container walls. While the in-house MATLAB model is also not

capable of including volumetric expansion, it is capable of estimating freezing asymmetry using real-world materials. Multiple tapered geometries will be studied and the deviation from a 1-D phase front will be determined.

VI.B. Convective Coupling Analysis

To date, all experimental investigations into solar thermal propulsion outside of this work have relied on sensible heat thermal energy storage (TES). While initial mentions of a latent heat thermal energy storage systems suggest benefits from an increase in energy storage density, they fail to elaborate on the benefits associated with constant temperature energy delivery. It is suggested that when considering the effective energy storage density of a medium (i.e. the fraction of stored energy that is usably delivered to a propellant stream) latent heat energy storage systems will deliver an improvement in performance beyond what is suggested by the energy storage density advantage alone.

Published data from the Integrated Upper Stage (ISUS) project lists propellant exit temperatures during hydrogen blowdown testing for their sensible heat Reciever-Absorber-Converter (RAC) module.[34] Figure 13 shows that the sensible heat system is able to deliver a relatively stable exit temperature for the first seven minutes of the burn despite the fact that cooling of the thermal energy storage medium is required for heat transfer into the propellant stream. The stable exit temperature is achieved by properly designing the length of heat exchanger channels through the thermal energy storage medium. Heat exchanger channels were sized so that the propellant gas was able to achieve thermal equilibrium with the energy storage medium before reaching the end of the channel when the RAC is at maximum temperature. As heat is drawn from the entrance area of the RAC unit, this equilibrium point simply shifts further and further downstream within the heat exchanger to maintain a stable exit temperature. Eventually, the equilibrium point for the propellant gas exists outside the heat exchanger and the gas exit temperature begins to follow the overall cooling curve of the RAC unit.

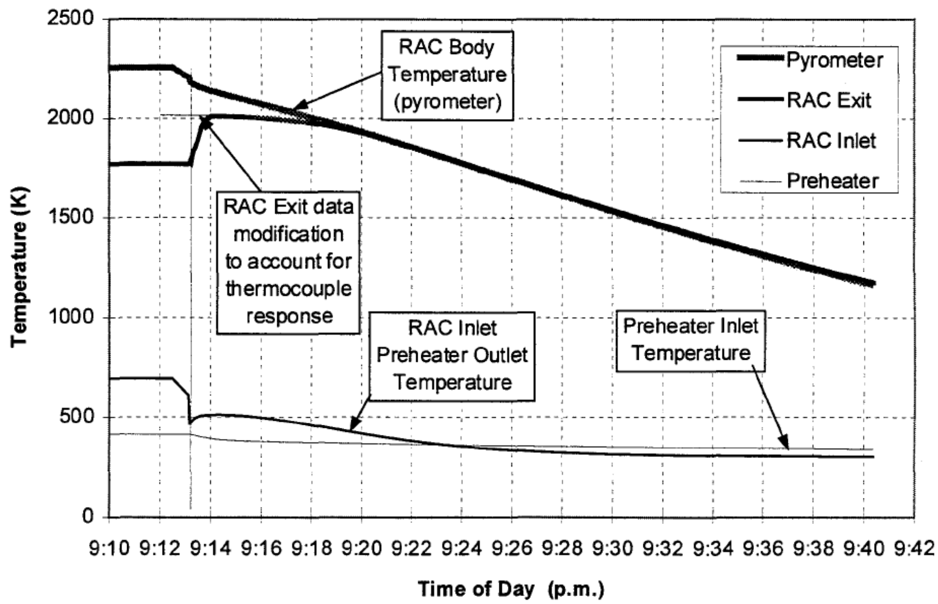

Figure 13: ISUS RAC experimental data from hydrogen blowdown testing. RAC exit temperature was measured at the outer surface of the exhaust tube which is assumed to be equivalent to the hydrogen exit temperature. Graph reprinted from Frye and Kudija[34]

The ISUS design provides steady thrust performance, but the effective energy storage density of such a system is lowered by the use of oversized channels. The ISUS RAC contains 20 kg of graphite and 15 kg of rhenium TES mass, corresponding to an energy storage density of approximately 0.72 MJ/kg assuming a 600 K overall operating range (double the allowable design ΔT for thermal electric conversion[35]). If the

American Institute of Aeronautics and Astronautics

first seven minutes of the burn in Figure 13 are considered the “usable portion,” the total energy transfer to the hydrogen propellant calculated using the published data is approximately 14.5 MJ. This would yield an effective energy density for the ISUS RAC of only 0.46 MJ/kg.

In the case of a latent heat system, the thermal energy storage medium remains at a relatively constant temperature during heat release and the corresponding heat exchanger can be designed without the additional length required by a sensible heat system. Reducing the length will compound the energy storage density gains that are already achieved simply by switching to a higher performance latent heat material.

Future efforts in this work will focus on demonstrating the energy coupling advantages of using a latent heat storage system. Commercial multiphysics software is being used to create a model for a single RAC heat exchanger channel and COMSOL work at UCCS has already demonstrated the appropriate sensible heat coupling behavior. The multiphysics model will be altered to incorporate phase change material (PCM) based storage using the temperature transforming method and performance will be compared. By gradually reducing the length of the PCM based heat exchanger until similar performance is achieved, a theoretical basis will be developed for convective coupling assumptions.

Concurrent with the modeling effort, a final series of experiments using the USC solar furnace will be conducted to couple a gas stream to both sensible and latent heat energy storage mediums. These experiments will attempt to mirror those performed during the ISUS program albeit at a lower temperature and for a single heat exchanger channel. Coupling a gas stream with silicon thermal energy storage will provide experimental validation for the use of high temperature PCMs and will represent the most significant experimental work to date.

VI.C. Potential Solar Furnace Improvements

The end-to-end system efficiency of the USC solar furnace is relatively low at approximately 40%. Table 2 lists the individual component efficiencies for the furnace and their relevant contributing factors. The heliostat and the quartz chamber window are the least efficient components of the system since they suffer from both transmission and reflectance losses. The heliostat, which uses commercial second surface soda-lime glass mirrors, is not optimized for solar reflection and represents the weakest component in the system. The quartz window is also a major loss contributor despite a high transmittance in the solar spectrum due to reflection losses brought on by the relatively steep incident angle of rays from the solar concentrator. For future testing, it is possible to substantially raise the performance of the furnace facility by replacing the heliostat mirrors with higher cost first surface mirrors and employing a secondary concentrator to achieve higher concentration ratios.

Table 2: Component efficiencies of the USC solar furnace

Component	Approx. Efficiency	Contributing Factors
Heliostat Mirrors	68%	Reflection Losses
		Transmission Losses
		Weathering
		Solarization
		Surface Imperfections
		Dirt
Concentrator Mirrors	90%	SiO_2 Coating Transmittance
		Aluminum Reflectivity
Quartz Window	73%	Reflection Losses
		Transmission Losses
1” Acceptance	90%	Spherical Abberations
		Experimental Design
Total	**40%**	

VII. Conclusions

A bi-modal solar thermal microsatellite bus has been identified as a promising configuration for missions requiring a substantial ΔV. By using a high performance thermal energy storage medium (TESM), the solar thermal concept can be scaled to microsatellites where stability and energy density benefits result in a large ΔV capability ($> 1\ km/s$). Both silicon and boron have been have been suggested in the literature as potential TESM materials for a high performance bi-modal configuration. However, a lack of developmental history has precluded their inclusion into solar thermal designs. The goal of this research effort is to provide an experimental and analytical background for high temperature latent heat thermal energy storage and provide a road map for future work with this enabling technology. To date, experimental efforts have succeeded in constructing a viable solar thermal testing facility and conducting experiments using molten silicon as a TESM. These experiments have demonstrated practical concerns with using silicon as a PCM including the effects of density change and material compatibilities. Additionally, models have been created to determine the macro properties of a silicon based system and have demonstrated sufficient predictive capability for experimental design without a rigorous treatment of the phase change process. Future work is focused on improving the capability of predictive modeling and considering the effects of coupling a propellant stream with a latent heat storage medium. The ultimate goal of this research will be to produce an experimental data set coupling a propellant stream to silicon based thermal energy storage system bringing high temperature latent heat thermal energy storage to the same development level as sensible heat systems.

Acknowledgments

This work was funded by the United States Air Force Research Laboratory, Aerospace Systems Directorate. M.R. Gilpin would also like to the ARCS Foundation for their support.

References

[1]Scharfe, D. and Ketsdever, A., "A Review of High Thrust, High Delta-V Options for Microsatellites Missions," *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, No. AIAA-2009-4824, American Institute of Aeronautics and Astronautics, Denver, CO, August 2009.

[2]Gilpin, M., Scharfe, D., Young, M., and Pancotti, A., "Molten Boron Phase-Change Thermal Energy Storage: Containment and Applicability to Microsatellites," *42nd AIAA Thermophysics Conference*, No. AIAA-2011-3637, American Institute of Aeronautics and Astronautics, 2011.

[3]Gilpin, M., Scharfe, D., Young, M., and Pancotti, A., "Molten Boron Phase-Change Thermal Energy Storage to Augment Solar Thermal Propulsion Systems," *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, No. AIAA-2011-5986, American Institute of Aeronautics and Astronautics, San Diego, CA, 2011.

[4]Scharfe, D., Young, M., Gilpin, M., and Rexius, T., "Augmentation of Solar Thermal Propulsion Systems via Phase Change Thermal Energy Storage and Thermal Electric Conversion," *Space Propulsion 2012*, No. unknown, unknown, unknown, unknown 2012.

[5]Gilpin, M., Scharfe, D., and Young, M., "Phase-Change Thermal Energy Storage and Conversion: Development and Analysis for Solar Thermal Propulsion," *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, No. AIAA-2012-3715, American Institute of Aeronautics and Astronautics, Atlanta, GA, 2012.

[6]Gilpin, M. R., Scharfe, D. B., Young, M. P., and Webb, R. N., "High Temperature Latent Heat Thermal Energy Storage to Augment Solar Thermal Propulsion for Microsatellites," *11th Annual AIAA Southern California Aerospace Systems and Technology (ASAT) Conference and Banquet*, Santa Ana, CA, May 2014.

[7]Carroll, J., "Solar Orbit Transfer Vehicle," *AIAA Space Conference*, No. AIAA-2000-5110, American Institute of Aeronautics and Astronautics, Long Beach, CA, 2000.

[8]Kennedy, F. and Jacox, M., "The Integrated Solar Upper Stage (ISUS) Program," *AIAA 1995 Space Programs and Technologies Conference*, American Institute of Aeronautics and Astronautics, Huntsville, AL, September 1995.

[9]Lide, D. R., *CRC Handbook of Chemistry and Physics*, Boca Raton, FL, 77th ed., 1996.

[10]Chase, M. W., editor, *NIST-JANAF Thermochemical Tables 2 Volume-Set (Journal of Physical and Chemical Reference Data Monographs)*, American Institute of Physics, 1998.

[11]Ho, C., Powell, R., and Liley, P., "Thermal Conductivity of the Elements: A Comprohensive Review," *Journal of Physical and Chemical Reference Data*, Vol. 3, 1974.

[12]Koyama, K., "Thermal Conductivity of Magnesium Flouride Between 25 and 900 C," *Journal of the American Ceramic Socitey*, Vol. 52, No. 4, June 2006.

[13]Glassbrenner, C. and Slack, G. A., "Thermal Conductivity of Silicon and Germanium from 3 K to the Melting Point," *Physical Review*, Vol. 134, No. 4A, May 1964, pp. A1058–A1069.

[14]Shoji, J. M., Frye, P. E., and McClanahan, J. A., "Solar Thermal Propulsion Status and Future," *AIAA Space Programs and Technologies Conference*, Huntsville, AL, March 1992.

[15]Laug, K. K., Holmes, M. R., and Westerman, K. O., *Solar Bi-Modal System Concept: Mission Applications, A Preliminary Assessment*, Technical Paper, Air Force Research Lab Propulsion Directorate, Wright-Patterson AFB, OH, 1992.

[16]Abbott, R., "MultiUse Solar Thermal Power Generators," *Space Technology and Applications International Forum*, Alburquerque, NM, February 2001.

[17]Kennedy, F. and Palmer, P. L., "Preliminary Design of Micro-Scale Solar Thermal Propulsion System," *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, No. AIAA-2002-3928, American Institute of Aeronautics and As-

tronautics, Indianapolis, IN, July 2002.

[18]Colonna, G., Capitta, G., Capitelli, M., Wysong, I., and Kennedy, F., "Model for Ammonia Solar Thermal Thruster," *Journal of Thermophysics and Heat Transfer.*, Vol. 20, No. 4, October-December 2006.

[19]Laug, K., "The Solar Propulsion Concept is Alive and Well at the Astronautics Laboratory," *JANNAF Propulsion Meeting*, Cleaveland, OH, May 1989.

[20]Michalsky, J. J., "The Astronomical Almanac's Algorithm For Appoximate Solar Position (1950-2050)," *Solar Energy*, Vol. 40, No. 3, 1988, pp. 227–235.

[21]Meeus, J., *Astonomical Algorithms*, Willmann-Bell, Inc., 2009.

[22]Woodall, "Energy Conversion," US Patent No. 4,316,048, 1982.

[23]Chubb, D. L., Good, B. S., and Lowe, R. A., "Solar Thermophotovoltaic (STPV) System With Thermal Energy Storage," *The 2nd NREL Conference on Thermophotovoltaic Generation of Electricty*, Colorado Springs, CO, July 1995.

[24]Datas, A., Chubb, D., and Veeraragavan, A., "Steady State Analysis of A Storage Integrated Solar Thermophotovoltaic (SISTPV) System," *Solar Energy*, Vol. 96, 2013, pp. 33–45.

[25]Kennedy, F., *Solar Thermal Propulsion for Microsatellite Manouevering*, Doctoral thesis, University of Surrey, Guildford, Surrey, UK, September 2004.

[26]Hollahan, J. R. and Gregory, N., "A Torsion Effusion Study of the Reaction of Grahpite with Oxides of Thorium and Zirconium," *The Journal of Physical Chemistry*, Vol. 68, August 1964, pp. 2346–2351.

[27]Rhim, W.-K. and Ohsaka, K., "Thermophysical Properties Measurements of Molten Silicon by High-Temperature Electrostatic Levitator: Density, Volume Expansion, Specific Heat Capacity, Emissivity, Surface Tension and Viscosity," *Journal of Crystal Growth*, Vol. 208, 1999, pp. 313–321.

[28]Oswald, M., Turek, M., and Bagdahn, J., "Numerical Simulations of Thermo-Mechanical Stresses During The Casting of Multi-Crystaline Silicon Ingots," *11th. Int. Conf. on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems*, Bordeaux, France, April 2010.

[29]Ciszek, T. F. and Schwuttke, G. H., "Method for Directional Solidification of Silicon," US Patent No. 4,243,471, 1981.

[30]Ciszek, T., Schwuttke, G., and Yang, K., "Directionally Solidified Solar-Grade Silicon Using Carbon Crucibles," *Journal of Crystal Growth*, Vol. 46, 1979, pp. 527–533.

[31]Elgafy, A. and Mesalhy, O., "Numerical and Experimental Investigations of Melting and Solidification Processes of High Melting Point PCM in a Cylindrical Enclosure," *Journal of Heat Transfer*, Vol. 126, October 2004, pp. 869–875.

[32]Amundson, T. R., *Computational Evaluation of the Effects of Voids on a Thermal Energy Storage System in a Combined Solar Power and Propulsion System*, Master's thesis, University of Colorado Colorado Springs, 2013.

[33]Reid, M. R., Scharfe, D. B., and Webb, R. N., "Computational Evaluation of a Latent Heat Energy Storage System," *Solar Energy*, Vol. 95, 2013, pp. 99–105.

[34]Frye, P. E. and Kudija, C., "Integrated Solar Upper Stage Engine Ground Demonstration Test Results and Data Analysis," *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, No. AIAA-1998-3958, American Institute of Aeronautics and Astronautics, 1998.

[35]Miles, B. J., "Development and Testing of High Temperature Coatings for the Integrated Solar Upper Stage Thermal Energy Storage System," *Space Technology and Applications International Forum*, Alburquerque, NM, January 1997.